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Project Director(s) R. B. Gray

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PROGRESS REPORT

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6. AUTHOR(S) OF REPORT: R.B. Gray, J.I. Craig, S.V. Hanagud, J.J. Harper, S. Klein, N.M. Komerath, S.G. Lekoudis, H.M. McMahon, S.A. Meyer, G.A. Pierce, A.D. Reddy, N.L. Sankar, L.W. Rehfield and J.C. Wu

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

Publications:

1. Wang, C.M., Wu, J.C., and Sankar, N.L., "Unsteady Aerodynamics of Airfoils Oscillating In and Out of Dynamic Stall", AIAA Paper 85-4078. Presented at the Third Applied Aerodynamics Conference, Colorado Springs, Colorado, October 1985.

2. Wu, J.C, Hsu, T.M., Tang, W. and Sankar, N.L., "Viscous Flow Results for the Vortex-Airfoil Interaction Problem", AIAA Paper 85-4053. Presented at the Third Applied Aerodynamics Conference, Colorado Springs, Colorado, October 1985.

3. Wake, B.E., Sankar, N.L. and Lekoudis, S.G., "Computation of Rotor Blade Flows Using the Euler Equations", AIAA Paper 85-5010. Presented at the Third Applied Aerodynamics Conference, Colorado Springs, Colorado, October 1985.

4. Wu, J.C., "Boundary Element Methods and In Homogeneous Elliptic Differential Equations", Boundary Elements VII, Vol. 2., pp. 9-95, Springer-Verlag, 1985.

5. Komerath, N.M., McMahon, H.M., and Hubbartt, J.E., "Aerodynamic Interactions Between a Rotor and Airframe in Forward Flight", AIAA Paper No. 1606, 18th Fluid Dynamics, Plasmadynamics and Lasers Conference, Cincinnati, Ohio, July 1985.

6. McMahon, H.M., Komerath, N.M., and Hubbartt, J.E. "Studies of Rotor-Airframe Interactions in Forward Flight", AIAA Paper No. 85-50-15, Third Applied Aerodynamics Conference, Colorado Springs, CO, October 1985.

7. Komerath, N.M., Thompson, T.L., and Gray, R.B., "Velocity Measurements in the Near Wake of a Hovering Rotor", AIAA Paper 85-1675, presented at the 18th Fluid Dynmamics, Plasmadynamics and Lasers Conference, Cincinnati, Ohio, July 1985.

8. Komerath, N.M., Thompson, T.L., and Gray, R.B., "Velocity Measurements in the Near Field of a Rotor Blade in Hover", AIAA Paper No. 85-5013, presented at the 3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 1985.

4. Rehfield, L.W. and Reddy, A.D., "Observations on Compressive Local Buckling, Postbuckling and Crippling of Graphite-Epoxy Airframe Structure," AIAA/ASME/ASCE/AHS 27th SDM Conference, San Antonio, Texas, May 19-21, 1986. (Accepted for Presentation and Publication in the Proceedings).

9. Rehfield, L.W., "Design Analysis Methodology for Composite Rotor Blades," proceedings of the Seventh Conference on Fibrous Composites in Structural Design, AFWAL-TR-85-3094, Dec. 1985, pp. (V(a)-1) - (V(a) - 15).

10. Jonnalagadda, V.R.P., and G.A. Pierce, "Nonlinear Deformation of Rotating Beams -- An Alternate Method of Formulation," published in the Journal of the American Helicopter Society, Vol. 30, No. 2, 1985.

11. Hodges, D.H., D.A. Peters, G.A. Pierce, and V.R.P. Jonnalagadda, "Comment on 'Nonlinear Deformation of Rotating Beams - An Alternate Method of Formulation," submitted for publication to the Journal of the American Helicopter Society.

12. Jonnalagadda, V.R.P., and G.A. Pierce, "Effect of Cyclic Pitch Variations on Hingeless Rotor Blade Stability," presented at the ARO Dynamics and Aeroelastic Stability Workshop, Atlanta, Georgia, December 4-5, 1985.

13. Hanagud, S.V., "Elastic Fuselage Modes and Higher Harmonic Control," paper presented and published in the proceedings of the Eleventh European Rotorcraft Forum, London, Sept. 1985.

<u>Presentations</u>:

1. Bauchau, O., Coffenberry, B.S. and Rehfield, L.W., "A Comparison of Composite Rotor Blade Models," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, Georgia, December 4-5, 1985.

2. Hodges, R.V., Nixon, M.W., and Rehfield, L.W., "Comparison of Composite Rotor Blade Models: Beam Analysis and an MSC Nastron Shell Element Model," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, Georgia, December 4-5, 1985.

3. Rehfield, L.W., "Shear Center, Elastic Axis and Their Usefulness in Evaluating Composite Rotor Blade Response," ARO Dynamics and Aeroelastic Stability Modeling Workshop, Georgia Institute of Technology, Atlanta, Georgia, December 4-5, 1985.

4. Rehfield, L.W., "Modern Composite Helicopter Rotor System Structures," Symposium to Honor Nicholas J. Hoff on his 80th birthday, Stanford University, Stanford University, Stanford, California, January 3, 1986.

5. Jonnalagadda, V.R.P., and G.A. Pierce, "Effect of Cyclic Pitch Variations on Hingeless Rotor Blade Stability," presented at the Technical Workshop: Dynamics and Aeroelastic Stability Modeling of Rotor Systems, Atlanta, Georgia, December 4-5, 1985.

6. Hanagud, S.V., "Finite Difference Techniques for Rotor Blade Equations," ARO Dynamics and Aeroelastic Stability Modeling, Atlanta, Georgia, December 4-5, 1985.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

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Post Doctors: V.R. Anand, A. Chattopadhyay, M. Meyyappa, & C. Wang

Fellows: Ph.D.: Albert G. Brand, Dimitrios N. Mavris, Thomas L. Thompson, Dana J. Taylor, Brian Wake

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M.S.: B. Glass, R. Jolly, J. L. Kemnitz, L.S. Mayer, H.E. Mersinoglou, R. Srivastava

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DEGREES AWARDED THIS REPORTING PERIOD:

A.G. Brand	MS - Sept. 1985
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V.M. Kaladi	MS - Sept. 1985
Y.K. Kim	MS - Sept. 1985
S.G. Liou	MS - Sept. 1985
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P.L. Oliver	MS - Sept. 1985

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A.G. Brand	MS - Sept. 1985	PhD Program Georgia
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C. Boyette	MS - Dec 1983	Hughes Helicopters
C. Brevoort	MS - Sept 1983	Lockheed Georgia
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H.P. Chen	PhD- Dec 1983	Georgia Tech
MAJ M. Clifford	MS - Dec 1982	US Army
J.E. Corban	*BAE-June 1983	Hughes Helicopters, Inc
P.L. Elliot, III	*BAE-June 1983	Boeing Vertol Co.
K. Engelhardt	MS - Sept 1983	Hughes Helicopters, Inc
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C. Grimmell	MS - June 1984	General Dynamics
B.A. Gustavson	MS - Sept 1982	Kaman Aerospace
MAJ W. J. Hatch	MS - June 1984	US Army
J.A. Humphries	MS - June 1984	US Air Force
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CPT W. McArthur	MS - March 1983	US Army
P. Oliver	MS - June 1985	Hughes Helicopters, Inc.
D. O'Neil	MS - Sept 1984	Hughes Helicopters, Inc.
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G. Power	MS - Sept 1983	United Technologies Research Center
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J. Rogers	MS - Sept 1983	General Dynamics
S. Sparks	MS - Sept 1983	United Technologies Research Center
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T. Thompson	MS - Sept 1983	PhD Program Georgia Tech
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*Completed one or more Helicopter related courses.

RESEARCH TASKS

I. Aerodynamics

Task 1. Experimental Studies for Tip Vortex Core Modeling

R.B. Gray, N.M. Komerath, T.L. Thompson, J.L. Kemnitz, O. Kwon

The objectives of this task are to develop a capability for measuring the flow field near the tip and in the wake of a hovering helicopter model rotor using a laser velocimeter and to use the data to guide the development of a tip vortex core model for use in free wake analyses for blade loading predictions. The longer term objectives are to develop a hovering vortex wake analysis which is not as dependent on empirical parameters for describing the tip vortex geometry and to investigate the extension of the vortex wake analysis to low-speed forward flight.

During the last reporting period, progress has been made on several aspects of the problem. Previous experiments had demonstrated the feasibility of measuring velocity profiles in the vortex core using an off-axis light receiving system. However, the problem of having to re-align the receiving optics for each measuring location put severe limits on the ability to make extensive measurements. To solve this problem, an automated off-axis receiving system, the first of its kind reported, has been designed and the components are on order. The system as designed utilizes an automated traverse with two rotational degrees of freedom and one linear traverse for focusing the front lens. The receiving optics will be made to follow the movements of the measuring volume under computer control. Fine adjustments as required will be performed using motorized micrometers attached to the light sensors, and controlled by the operator. At present, the optics modules involved have been purchased and have been set up and tested satisfactorily. The automated stages are expected to be received shortly. The system design also anticipates extensive use in wind tunnel tests where the higher signal-to-noise ratio of this system will be used to improve and accelerate data acquisition using the laser velocimeter.

Following successful demonstration in the 7'x9' Forward Flight facility a new atomizer seeder was used in the Hover facility. This enabled extensive measurements of the flowfield in the close vicinity of the rotor blade in order to study the origin of the tip vortex. A large data base has been accumulated, and some results were presented at the AIAA Applied Aerodynamics Conference in October.

In order to estimate and quantify errors due to centrifugal effects on seed particles, efforts are being devoted to the measurement of particle size in the flowfield. Tests are under way to determine particle size using measurements of sink rate and scattering intensity ratios at different viewing angles.

Since an accurate visualization of the trajectory and steadiness of the vortex core will be of great help in interpreting the point measurements made using the LDV, the technique of dynamic laser sheet visualization is being applied to the flowfield. To date, this technique has been successfully used to clearly see the core of the vortex. This will be extended to precisely locate the position and trajectory of the core using photographic measurements. This may also provide data on the amount of unsteadiness, if any, in the vortex position.

Task 2. Modification of Blade Tip Loading to Improve Hovering Figure of Merit
R.B. Gray & T. Thompson

Measured pressure distributions on the tip of a hovering model rotor blade show a low pressure region which is associated with the roll-up and rearward sweep of the tip vortex over the trailing 50% for the blade upper surface. This low pressure region near the trailing edge contributes significantly to the section pressure drag and hence to the rotor power required. The objective of this task is to explore the possibilities of improving performance by modifying the tip pressure distribution.

This research task has been completed and a final report will be prepared.

Task 3. The Prediction of Flow Around Blade Tips
R.B. Gray, S.G. Lekoudis, B.E. Wake

The objective of this task is to develop a procedure to accurately predict the flow field, and hence the airloads in the vicinity of the tip of a rotor blade. This requires a correct prediction of the vortex formation and roll up processes and the strength and location of any shocks.

During this reporting period a National Science Foundation grant was obtained with the title "Computing Blade Flows Using the CRAY X-MP" The grant provides 25 hours of CRAY X-MP time to computer blade flows. The requested computer is the Boeing Computer Services Cray. The available time has been used since the Fall of 1985.

Another NSF grant was obtained under which B.E. Wake participated, for the period of 30 days, in a workshop involving supercomputing at Boeing (Seattle). During that time special instruction on code vectorization was provided by the Boeing Computer Services. The blade Euler code was vectorized. Also Cray Research Inc. offered computer time on one of their CRAY X-MP's. The Cray-Research Inc. is interested in keeping informed about the impact of CFD in the helicopter industry.

In October 1985 the AIAA paper 85-5010, "Computation of Rotor Blade Flows Using the Euler Equations," by Wake, Sankar and Ledoudis, was presented at the 3rd Applied Aerodynamics Conference in Colorado Springs, Colorado.

The Euler code was further developed into a Navier-Stokes solver, for three-dimensional, unsteady compressible flows, by adding the viscous terms. Low Reynolds number (up to 10,000) results for lifting configurations in hover were obtained. Different grid studies are being carried out.

In December, the Euler code was transferred to Bell Helicpters, Inc.

Task 4. Studies of Unsteady Rotor Aerodynamics
J. C. Wu, N.L. Sankar & C. Wang, C. Fouts, J.R. Jolly, M.T. Patterson, R. Srivastava, W. Tang, I. Tuncer

The purpose of this task is to develop theoretical and computational tools for the prediction of the unsteady airloads on modern rotor blades in hover and in forward flight.

During this reporting period, the development of the 2-D incompressible Navier-Stokes solver has been completed for laminar flow conditions. Comparisons of computed aerodynamic loads for an oscillating airfoil with existing flow solvers and the streakling patterns with water tunnel observations show good agreement. (See publication #1)

The 2-D compressible Euler solver for predicting BVI phenomena has been extended to include viscous effects at high, turbulent Reynolds numbers. Calibration of this solver continued during the reporting period. Comparisons of the predictions of this solver with existing numerical data (Transonic Small-Disturbance theory, Full-potential, Euler and Thin Layer Navier-Stokes solvers) has been made. (See publication #2).

Under the support of the U.S. Army Aeroflightdynamics Directorate during the summer of 1985, the 3-D Euler solver for rotor configurations was vectorized for efficient computations on the CRAY XMP. This solver was also coupled to the free wake model from the CAMRAD code. Some preliminary results for the 3-D BVI phenomenon were obtained using the vectorized Euler solver. These 3-D BVI results are the first of their kind, and compare well with the experimental data of Carradonna and Tung. These results will be presented at the coming AHS Forum.

The 2-D compressible dynamic stall solver has been made available to the NASA Ames Research Center (Dr. Chee Tung, I.C. Chang), the NASA Lewis Research Center (Dennis Huff and L. Bober), and Bell Helicopter Textron.

Task 5. Studies of Airframe Flowfield in Forward Flight
H.M. McHahon, N.M. Komerath, A. Brand, D. Mavris, S. Liou, H. Mersinoglou

The long-term objective of this task is the development and validation of a reliable technique for predicting the coupling between rotor and airframe aerodynamics. The short term goals are to provide a data base for developing and assessing analytical models, to assess existing analytical models, and to investigate the flow features important in rotor-airframe aerodynamics.

The experimental data base of mean and periodic surface pressures has been studied to determine gaps in the data needed to be filled during the next wind tunnel entry. Several features of the interaction flowfield were observed and are described in AIAA paper no. 85-5015.

A second hub design for the direct measurement of rotor thrust was tested but the results were not satisfactory. The data indicated that the design concept seemed sound but that there was excessive shaft and hub vibration. Accordingly, an improved shaft has been fabricated with more emphasis on balancing and the thrust hub is being balanced by an off-campus specialist.

The AMI (Clark-Maskew) code has been run to evaluate its ability to predict the measured surface pressures on the cylindrical airframe as well as velocities in the rotor wake. Time-averaged velocities measured using the LDV along three horizontal lines in the wake above the airframe were compared with predicted values. The streamwise component showed fair agreement but the vertical component did not agree well. The correlation between the predicted and measured mean surface pressures was not considered satisfactory. The developers of the code have indicated that they feel that newer versions of the code can make better predictions, but none have yet been demonstrated. With the available version of the code, the solution does not converge to a unique skew angle for the wake. To investigate the reason for this, the off-body velocity scanning capability of the code was tested using an infinite cylinder model in crossflow, a case where an analytical solution is available. It was found that potentials and surface velocities were accurately computed, but that the off-body velocity calculations were in error. Accordingly, new subroutines are being developed to improve these calculations. Since the data has shown the need to incorporate periodic fluctuation effects in the wake model, the possibility of using advanced rotor wake models in conjunction with the AMI body code is being pursued. Additional efforts during the last reporting period have been devoted to improving data reduction capabilities, and have resulted in the addition of graphics routines for more rapid comparison of analytical and experimental results. In the next reporting period, testing will be resumed after calibration of the tunnel force balance system is completed.

II. Structures

Task 1. Structural Dynamic System Identification

S.V. Hanagud, J.I. Craig, N.S. Abhyankar, A. Chattopadhyay, M. Meyyappa, Y. Cheng, M. Obal, S. Sarkar, O.J. Kwon, and Y.K. Yillicki

The purpose of this task is to develop an approach to advance the state of the art in airframe structural dynamic modeling. Development of applicable system identification techniques - the mathematical model of the system of interest - and improved physical models are the basis for this research.

During the first three years research in this task were largely restricted to developments of techniques for structural dynamic system identification. During the fourth year, in addition to basic research specific applications of system identification techniques to rotorcraft, aeromechanics and control problems have been studied. Specific areas of study are as follows.

(1) Application of structural dynamic system identification techniques to study fuselage vibrations of aircraft with the implementation of higher harmonic control.

(2) Development of finite difference techniques to study rotor blade equations. This development is to develop a technique of structural dynamic system identification techniques for rotor blades.

(3) Development of identification techniques to accommodate varying non-structural masses. Cantilever beam test results and tailboom test results have been used to compare diferent identification techniques.

(4) A Lagrange multiplier technique is being developed to be able to identify system with nonproportional damping with large degrees of freedom.

Task 2. Crashworthy Characteristics of Composite Rotorcraft Structures

S.V. Hanagud, R. Chander, B. Glass, L.S. Mayer, P. Sriram and W. Zhou

The objective of this task is to conduct basic research to develop improved techniques and procedure for designing crashworthy composite structures for rotorcraft. This objective includes the development of testing techniques and optimization of the crashworthy designs under the constraints of weight restrictions, cost and performance requirements.

During the first three years the research work in the field included the development of test facilities and some of the techniques for analysis. During this year research tasks are being directed towards specific fields that we can constitute and other labs and industries are not pursuing. The specific areas are as follows:

(1) Correlation of static test results with dynamic test results for energy absorbing structures.

(2) Analysis of energy absorption mechanism through the study of finite deformation analysis by using finite element methods with arc length iteration techniques.

(3) Modification to KRASH type of program to include energy absorption mechanism.

(4) Development of techniques for the analysis of occupant motion and occupant forces by using Kanis' method.

(5) Optical techniques for whole field out-of-plane displacement measurement.

(6) Techniques and criteria for the design of present rotorcraft crashworthiness.

A National Specialists' meeting is being organized during April 7-9, 1986, At Georgia Tech. We have selected approximately 35 papers to be presented at the meeting.

Task 3. Concepts for Stability Critical Airframe Structures
A.D. Reddy, L.W. Rehfield, and L.K. Daniel

This task is concerned with crippling and postcrippling behavior of thin walled graphite/epoxy composite airframe members in axial compression. The main objectives are to i) generate an experimental data base on the crippling and postcrippling behavior, ii) develop simple analytical methods to predict these behavior, and iii) provide better insight into the failure processes for this type of structure.

Three important issues are currently being addressed. The first is the influence of transverse shear deformation on local buckling and postbuckling behavior. A new, simple theory has been developed which agrees well with more complex theories and our experiments. The second, the influence of nonlinear material behavior, is under investigation. The third, crippling failure prediction, is a key issue. Progress has been made, but a final criterion is not defined as yet.

Task 4. Composite Rotor Blade Modeling
L. W. Rehfield

The theory for composite rotor blades that was begun under grants from the Army Aeromechanics Laboratory and the Army Structures Laboratory has been completed. The results are extremely interesting and suggest that elastic tailoring offers considerable potential. A demonstration example study has been conducted which illustrates the magnitude of control the designer may exercise by choosing ply layup and orientation.

Although rotor blades were some of the earliest structures in production from composites, the use of composites was primarily to increase fatigue life. Little work had been devoted to elastic tailoring of rotor blades until the recent efforts of the Army Aerostructures Directorate and the Georgia Institute of Technology. To date the following progress has been made:

1. A first approximation, single cell rotor blade model has been developed for composite designs and favorably compared recently with NASTRAN finite element simulations and static experiments conducted at Rensselaer Polytechnic Institute.

2. The physical basis for modeling, particularly after the ARO sponsored workshop entitled "Dynamics and Aeroelastic Stability Modeling of Rotor Systems," is now firmly established.

3. The next step is to proceed to a multicell theory and to explore the influence of elastic coupling on dynamic behavior.

III. Aeroelasticity

Task 1. Helicopter Vibration Suppression Techniques

G.A. Pierce, V. Anand, V.R.P. Jonnalagadda,
V. M. Kaladi, Y.K. Kim & D.J. Taylor

This program is intended to develop and validate comprehensive vibratory loads analyses for the evaluation of vibration suppression techniques. The loads analyses will be applicable to nonuniform multi-bladed systems with various hub constraints. Special emphasis will be placed on blade structural dynamics, hub and mast dynamics, and unsteady blade aerodynamics.

During this reporting period, the previously developed blade response analysis which incorporated a unique undeformed/deformed blade coordinate transformation was used to determine both stability and response characteristics of a hingeless rotor in forward flight. It was shown that the explicit representation of cyclic pitch effects in the transformation has a significant effect on both the stability boundary and the dynamic loads of forward flight. These results have been presented at the ARO sponsored workshop entitled "Dynamics and Aeroelastic Stability Modeling of Rotor Systems" and will be published in the AHS Journal in 1986.

A parallel formulation of the aeroelastic equations of motion is being completed at this time. This simulation is based on a combined modal (spatial) and harmonic (temporal) representation of the blade dynamics. The analysis incorporates the effects of both collective and cyclic pitch at all admissible harmonics. As a consequence this analysis will permit an accurate evaluation of approximate unsteady aerodynamic representations since it can utilize the exact (linear) aerodynamic representations of potential flow. In addition to the aerodynamic evaluation this method is ideally suited for the application of higher harmonic control techniques of vibration suppression.

Another development in the area of structural dynamics of rotor blades has been a preliminary study of bearingless blade restraints. The two methods which have currently been applied to uniform beams in torsion entail: 1) the matching of two beams as a nonhomogeneous boundary value problem; and, 2) a holonomic constraint simulation of a single beam at an intermediate point. These simple cases have proven to be successful and are being applied to more blade-like configurations.

A study has been conducted for the evaluation an improvement of aerodynamic representations which are currently being utilized in helicopter vibration analyses. A two-dimensional incompressible unsteady aerodynamic theory has been developed to treat the arbitrary motion of a thin airfoil in a freestream whose velocity can be a function of time. This theory has been applied to the problem of harmonic stream speeds in conjunction with harmonic airfoil oscillations. The results have been correlated with the approximate method of Greenberg and the more approximate representation of quasi-steady aerodynamics. A presentation of these findings will be published in the AHS Journal in 1986.

FACILITIES/EQUIPMENT

Laser Doppler Velocimeter (LDV) Data Acquisition System

N.M. Komerath, R.B. Gray, H.M.McMahon

The four-beam, two color Laser Doppler Velocimeter (LDV) consists of a five-watt Argon Ion Laser, modular optics, a three axis traversing system, and two counter-type signal processors directly interfaced into the memory of a dedicated HP1000 computer system. Two orthogonal components of flow velocity can be measured simultaneously and nonintrusively with a spatial resolution of 0.1 millimeters from a distance of over 2200mm. Frequency shifting on both channels enables measurement of the velocity vector in recirculating flows and a field stop system enables measurements close to solid surfaces.

During this reporting period, the LDV was used to continue measurements in the flowfield between the rotor and airframe in the Forward Flight Facility, after which it was transported back to the 9-foot Hover facility. Extensive measurements were made on the flow in the close vicinity of the rotor blade, and around the tip region where the tip vortex originates. By operating the system in the single-color mode, steady data rates of 3000 per second were attained with excellent signal quality.

An automated off-axis scatter light receiving system has been designed and ordered for rapid measurement of velocities in the tip vortex core using incense smoke particles too small to be sensed in back-scatter. The optics modules involved are now on hand and working, and the automated traverse components are expected soon.

The LDV is being used to perform in situ measurements of seed particle size by measuring settling velocities and angular distribution of scattered light. These measurements will be used to develop means of estimating and correcting for particle lag errors in vortex core velocity measurements.

The Argon Ion laser is being used to perform dynamic laser light sheet flow visualization studies to locate the trajectory of the tip vortex in order to aid in the efficient acquisition and interpretation of vortex core velocities. These studies will also assist in quantifying errors due to "vortex jitter", if any.

II. Nine-Foot Static Thrust Facility

R.B. Gray

The facility provides a laboratory-controlled environment for testing model helicopter rotors up to 4.5 feet in diameter in hovering flight. The LDV system described above is being used for data acquisition for Aerodynamics Task 1. The facility has also been used for Aerodynamics Task 2. The updating of this facility was to include the purchase of a modern data acquisition system and factory reconditioning of the mercury slipring assembly. Neither item has been a pressing matter. The reconditioning of the sliprings has been delayed to permit the testing to continue. The data acquisition system will not be purchased.

III. Structural Dynamic System Identification Facility

S.V. Hanagud & J.I. Craig

This laboratory is developed to measure, record, process, and analyze structural dynamic data for laboraoty model tests and field tests. The multichannel time series and structural dynamic analyzer allows acquisiton of data from one to eight channels simultaneously with the capability to expand to sixteen. The analysis software may run on the dedicated computer system or is portable to another system.

IV. Transient Dynamic Stress Analysis Facility

S.V. Hanagud & J.I. Craig

This facility is for the study of the dynamic behavior of structural components and assemblies under typical crash-induced loading situations for helicopters. The design of the facility involves a drop-test fixture for producing dynamic compressive loading of various metallic and composite test articles. A variety of waveform recorders acquire data during investigation of crashworthy characteristics of rotorcraft structures, particularly composite structures.

V. Seven-by-Nine Foot Forward Flight Facility

J.J. Harper, H.M. McMahon, & S. Klein

The closed low speed wind tunnel is the forward flight facility with a seven-by-nine foot test section. The design and installation of a powered model rotor system, fairings, floor, ceiling and honeycomb provide a total laboratory environment. The rotor system is mounted from the test section ceiling and fuselage models are mounted on a force balance sting. The Laser Doppler Velocimeter, a dedicated computer system and a modern force balance provide for data acquisition.

VI. Aeroelastic Rotor Test Facility

G.A. Pierce, S. Klein, M. Hashemi-Kia

The primary purpose of this facility is to permit scaled testing of rotor systems. Such tests are to be concerned with steady and unsteady aerodynamic phenomena, structural dynamic response behavior and aeroelastic stability characteristics. Model rotor systems of up to ten feet diameter can be accommodated.

During this reporting period, the equipment awarded under the "DoD University Research Instrumentation Program" has been acquired and installed in the facility. The total award was for $300,000 of which $60,000 were matching funds by Georgia Tech. The current capability of the data acquisition and test control systems will be described with appropriate observation of the DoD expansion.

Up to 40 channels of model-mounted transducer signals can be amplified by a rotating differential-amplifier package prior to being transmitted to the control room via the 52-channel slip-ring assembly. These signals plus others can be subsequently amplified by a bank of 48 (previously 12) NEFF amplifiers. Of these amplifier outputs 32 (previously 16) channels can be processed on-line by an analog-to-digital converter for transmission to the HP1000 A700 computer system. The HP1000 system has been expanded from 1 to 4 MB of memory and from 64 to 200 MB of disk storage.

The HP 1000 computer has a FORTRAN 77 compiler and three-dimensional graphics capability. In addition to the HP 2623A graphics terminal, system outputs can be recorded on an HP 2932A printer and HP7475A plotter. This output recording capability has been expanded to include a Tektronix memory oscilloscope with four channels of presentation. Also added to the system is a 16-channel digital-to-analog converter to provide test control signals generated by the HP 1000 system.

In addition to the 32 channels of data input to the HP 1000 system, another 16 channels can be received by a newly acquired Genrad 2515 CAT system. This 16 channel programmable system is capable of executing numerous spectural analysis operations on the incoming data. In addition the system includes the MODAL PLUS and SABBA software of SDRC. Thus the Genrad analyzer can conduct on-line modal and damping evaluations. The capability has been included to permit high speed data transfer between the Genrad 2515 and HP 1000 systems. Consequently, Genrad outputs can be presented by the printer and plotter or stored in the HP 1000 disk system. It is also possible to conduct off-line frequency analysis of any data residing on the HP 1000 disk system.

In addition to the expanded signal conditioning capabilities of the facility, the DoD award has permitted the installation of a three channel high-freqency hydraulic excitation system. This Zonic Excitation system will permit on-line computer control of a swashplate mechanism for the dynamic excitation and control of the model rotor system in blade pitch. Applications of this excitation system in conjunction with the expanded signal conditioning capability will permit on-line control and analysis of rotor system stability and response characteristics. The swashplate mechanism has been designed, constructed and operationally checked on a mock-up of the rotating shaft. It has recently been installed on the facility's drive shaft and is currently being made operational.

UPDATED AND NEW COURSE DEVELOPMENT

The updating of courses and the development of new courses that were listed in the contract have been completed. All courses have been taught at least once except for one updated course, Advanced Aeroelasticity II, which is offered on demand, and one new course, Unsteady Aerodynamics. The unsteady aerodynamics course is scheduled to be offered during the Spring of 1986. A summary of the status of these courses is shown in Table 1. The number indicating the students enrolled includes students in all disciplines in the A.E. Graduate Program. A measure of the interest in the Rotorcraft Program is indicated by the enrollment in the Rotorcraft Design course although the number given includes students not supported by the Center.

The rotor theory courses that were in existence when the Center was established continue to be taught. A summary of the enrollments is also attached as Table II. Again, the number of graduate students indicates the interest in the Rotorcraft Program and includes students who are self supported and supported by other means. The Introduction to Propeller and Rotor Theory course attracts a good number of undergraduate students, some of which interview and accept with the helicopter companies.

TABLE 1

Discipline	Course No.	Title	Updtd	New	Status	Instructor
Aerodynamics	4600*	Computational Aerodyn.		X	Sum. 1984 - 19**;Win.1985-9**	Sankar
	6012*	Viscous Flow III		X	Sum. 1983 - 7**;Sum.1984-20** Sum. 1985 - 11**	Lekoudis/ Strahle
	6022	Adv. Compress.Flow II	X		Spr. 1983 - 9** Spr. 1984 - 13**;Spr.1985-11**	Lekoudis Sankar
	6402*	Aerody. of Helicop.III		X	Sum. 1984 - 8**;Sum.1985-11**	Gray
	6802*	Num.Fluid Dyn.III		X	Fall 1983 - 11**;Fall '85-12**	Wu
	6810*	Unsteady Aerodynamics		X	Scheduled Spr. 1986	Wu
Aeroelasticity	6030	Adv.Potent.Flow I	X		Fall 1982 - 20**;Fall '83-17** Fall 1984 - 28**;Fall '85-26**	Pierce Pierce
	6031	Adv. Potent. Flow II	X		Win. 1983 - 17**;Win.1984-19** Win. 1985 - 21**	Pierce Pierce
	6200	Adv. Aeroelasticity I	X		Spr. 1983 - 8**;Spr.1984-11** Spr. 1985 - 11**	Pierce Pierce
	6201	Adv. Aeroelasticity II	X		Offered on demand	Pierce
	6202	Exp. Aeroelasticity	X		Sum. 1983 - 7**;Sum.1984- 7**	Pierce
Design	6350*	Rotorcraft Design I		X	Spr. 1984 - 13**;Win.1985- 9**	Schrage
	6351*	Rotorcraft Design II		X	Sum. 1984 - 7**;Spr.1985-12**	Schrage
Structures	4115*	Intro. Fiber Reinforced Composites		X	Fall 1984 - 20**;Fall '85- 9**	Rehfield
	4116*	Manuf. Compos. Struct.		X	Win. 1985 - 23**	Rehfield
	6106*	Finite Def. A/C Struct.		X	Sum. 1985 - 10**	Hanagud
	6132*	Vib. Meas. & Analysis		X	Sum. 1984 - 15**	Craig/ Hanagud
	6113*	System Identification		X	Sum. 1984 - 10**	Hanagud

* Proposed Course No.

**No. of Students Enrolled

CENTER OF EXCELLENCE
FOR
ROTARY WING AIRCRAFT TECHNOLOGY

EXISTING COURSES ENROLLMENT

AE 4400 Introduction to Propeller and Rotor Theory

Summer of 1982:	5 Graduate Students 10 Undergraduate Students
Fall of 1982:	8 Graduate Students 14 Undergraduate Students
Summer of 1983:	1 Graduate Student 6 Undergraduate Students
Fall of 1983:	9 Graduate Students 8 Undergraduate Students
Summer of 1984:	1 Graduate Student 5 Undergraduate Students 1 Special Student
Fall of 1984:	17 Graduate Students 22 Undergraduate Students
Summer of 1985:	3 Graduate Students 13 Undergraduate Students
Fall of 1985:	8 Graduate Students 15 Undergraduate Students

AE 6400 Rotor Aerodynamics I

Winter of 1983:	13 Graduate Students 3 Undergraduate Students
Winter of 1984:	7 Graduate Students 1 Undergraduate Student
Winter of 1985:	14 Graduate Students

AE 6401 Introduction to Helicopter Stability and Control

Spring of 1983:	10 Graduate Students 1 Undergraduate Student
Spring of 1984:	4 Graduate Students 1 Undergraduate Student
Spring of 1985:	14 Graduate Students

TABLE II

VISITS/COMMUNICATIONS

1. N.M. Komerath

   18th Fluid Dynamics, Plasmadynamics and Lasers Conference, Cincinnati, OH, July 13-19, 1985.

   3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 14-16, 1985.

2. S. Klein

   U.S. Army Aviation Applied Technology Directorate, Ft. Eustis, VA, July 22-24, 1985.

3. L.W. Rehfield

   NASA Langley Research Center, Hampton, VA, August 19-21, 1985.

   NASA Langley Research Center, Hampton, VA, November 14-16, 1985.

4. S. Hanagud

   NASA Langley Research Center, Hampton, VA 15-17, 1985.

   McDonnell Douglas Helicopter Company, Mesa, AZ, October 21-25, 1985.

5. J.C. Wu

   3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 14-16, 1985.

6. N.L. Sankar

   3rd Applied Aerodynamics Conference, Colorado Springs, CO, October 14-16, 1985

7. G.A. Pierce

   U.S. Army Aviation Applied Technology Directorate, Ft. Eustis, VA, September 30 - October 3, 1985.

SIGNIFICANT EVENTS

Computer Programs

The following helicopter computer codes are operational and are being used in various aspects of the Center's activities.

HESCOMP/VASCOMP	NASA/Boeing Vertol	Rotorcraft Sizing and Performance
C81	ARMY/Bell Helicopter	Compreshensive Helicopter Analysis
FLYRT	Hughes Helicopters	Flight Mechanics
DNAMO5	ARMY/Bell Helicopter	Vibration Analysis
SSP1/SSP2	ARMY	Single Rotor Helo Sizing and Performance
GTR	Bell Helicopter	Tilt Rotor Flight Mechanics Program
HOVER	ARMY Structures Lab	CFD Hover Analysis
HESS/FREEMAN	NASA/USARTL Langley	Rotor-Airframe Potential Flow
VASERO	NASA Ames	Coupled potential-boundary layer analysis
DYSCO	Kaman Aerospace	Dynamic System Coupler Code
FLIGHT DYNAMICS MICROCOMPUTER CODES	NSWL/Penn State	Dynamic Behavior of Single Rotor/Tail Rotor

Three student design teams comprised of CERWAT fellows and other graduate students with an interest in rotary wing engineering, captured First, Second, and Third Place in the Boeing Vertol/American Helicopter Society National Student Design Competition, "Design of a One-Man Rotary Wing Racer."

The Center and the U.S. Army Research Office co-sponsored a very successful technical workshop entitled, "Dynamics and Aeroelastic Stability Modeling of Rotor Systems," held on the campus of Georgia Tech on December 4 and 5, 1985, nearly 75 engineers from government, industry, and academia were in attendance.

Presentations

The following seminars were presented and well received at the Georgia Tech Center of Excellence:

"Application of Approximation Techniques to Helicopter Flight Path Optimization," Mr. Gilbert Boen, U.S. Army AVSCOM, August 29, 1985.

"Dynamic Systems Coupler and Higher Harmonic Control, MAJ Kip Nygren, U.S. Army, October 17, 1985.

"Analysis Technology at McDonnell Douglas Helicopter Company," Dr. Roger Smith, McDonnell Douglas Helicopter Company, October 22, 1985.

"Parameter Identification and Modern Control," Mr. Philip Fitzsimons, McDonnell Douglas Helicopter Company/Georgia Tech, October 31, 1985.

"Generalization of Hamilton's Law to a Bifilear Formulation with Application to Helicopter Stability," Mr. Amir Izadpanah, Georgia Tech, November 17, 1985.

Unsteady Aerodynamics of Airfoils Oscillating in and out of Dynamic Stall

C. M. Wang, J. C. Wu and L. N. Sankar
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

A solution procedure is presented for the computation of dynamic stall phenomena encountered by arbitrary shaped airfoils under arbitrary flow conditions. This procedure solves the unsteady, incompressible Navier-Stokes and the unsteady boundary layer equations using an efficient, zonal approach. A number of results for a modified NACA 0012 airfoil experiencing dynamic stall are presented and compared with available numerical data. Qualitative comparisons with flow visualization experiments are also presented. The present study also illustrates the effect of numerical viscosity on the accuracy and robustness of the solution procedure.

Viscous Flow Results for the Vortex-Airfoil Interaction Problem

J. C. Wu, T. M. Hsu, W. Tang and L. N. Sankar
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ABSTRACT

The unsteady airfoil-vortex interaction problem is analyzed using two solution procedures. In the first procedure, the unsteady, incompressible Navier-Stokes equations are solved in the vorticity-stream function form using an integro-differential formulation. In the second approach, the compressible Navier-Stokes equations are solved using an Alternating Direction Implicit (ADI) procedure. Both the approaches use a body-fitted coordinate system. The effects of turbulence are modeled using a two-layer eddy viscosity model. Numerical results are presented for the interaction of a passing vortex with a NACA 0012 airfoil and a NACA 64A006 airfoil for a wide range of flow parameters and compared with available numerical data.

Computation of Rotor Blade Flows Using the Euler Equations

B. E. Wake, N. L. Sankar and S. G. Lekoudis
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

ABSTRACT

The Euler equations are used to compute steady and unsteady three-dimensional transonic flows around nonlifting rotor blades. A hybrid numerical procedure is used that treats the spanwise derivative explicitly and the other spatial derivatives implicitly. The steady state results are in excellent agreement with results obtained from the full potential equation. The results for unsteady flow compare well with measurements. These results demonstrate the ability of the Euler solver to compute transonic flow around helicopter blades.

AERODYNAMIC INTERACTIONS BETWEEN
A ROTOR AND AIRFRAME IN FORWARD FLIGHT

N.M. Komerath, H.M. McMahon, and J.E. Hubbartt
Georgia Institute of Technology, Atlanta, Georgia

ABSTRACT

Prediction and understanding of the aerodynamic interactions between the rotor and airframe are essential to the improvement of rotorcraft design. Presented herein are results from initial phases of a comprehensive research program which focuses on validating codes for predicting these aerodynamic interactions. Mean and periodic pressures on the surface of a cylindrical body in the wake of a rotor at advance ratios of 0.075 through 0.20 and LDV data on the velocity components below the rotor plane are presented. The configuration is modeled using a prediction code reported in the literature and some comparisons are shown.

Accepted for presentation at the AIAA 18th Fluid dynamics and Plasmadynamics and Lasers Conference, Cincinatti, Ohio, July 16-18,

STUDIES OF ROTOR-AIRFRAME INTERACTIONS IN FORWARD FLIGHT

N.M. Komerath, H.M. McMahon, and J.E. Hubbartt
Georgia Institute of Technology, Atlanta, Georgia

ABSTRACT

The helicopter rotor and airframe cannot be treated in isolation if significant improvements in forward-flight performance are to be achieved; rotor-airframe interaction effects must be understood and predictable. Results from an experimental/analytical study of this interaction problem are presented and discussed. The experimental results include mean and periodic pressures on the surface of a cylindrical airframe and measured mean velocity components in the rotor wake. An existing prediction code is used to calculate mean pressures and velocity components which are compared with the experimental results. The impingement of the rotor wake on the airframe causes significant effects with regard to both the mean and periodic pressures. These mean effects are not adequately predicted by an available fully-coupled interaction code in its present form. A comprehensive prediction code must include unsteady effects.

VELOCITY MEASUREMENTS IN THE NEAR WAKE OF A HOVERING ROTOR

T.L. Thompson, N.M. Komerath, and R.B. Gray
Georgia Institute of Technology, Atlanta, Georgia

ABSTRACT

Current methods for rotorcraft flow field prediction require knowledge of the characteristics of the flow field in the near wake downstream of the rotor. The near wake presents a challenging measurement and modeling problem, involving steep and rapid fluctuations in velocity gradients, and a complicated system of vortices and vortex sheets.

The objectives of the experimental program being conducted at the Georgia Tech Static Thrust Facility are to measure the details of the core structure of the tip vortex in the near wake of a spinning rotor blade, and to validate analytical models for this core and its evolution. Along the way, however, various problems have to be surmounted, and various other characteristics must be established. These intermediate results will form the subject matter of this paper, which will also include some results of direct applicability to currently-used techniques for rotorcraft flow field and performance prediction. A section of the paper will also be devoted to description and discussion of the procedures for making these measurements using a Laser Doppler Velocimeter (LDV).

VELOCITY MEASUREMENTS IN THE NEAR FIELD OF A ROTOR BLADE IN HOVER

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Georgia Institute of Technology

ABSTRACT

Measurements of the velocity field close to a model rotor blade in hover are described. The flow around the tip of the blade has been emphasized in determining the measurement grid. A large data base has been constructed for quantitative comparison with predictions. The data has been used to construct qualitative pictures of the instantaneous flow field in several planes parallel and normal to the blade planform. Selected plots of velocity components measured during the passage of the blade have also been presented for quantitative comparison with prediction techniques. Preliminary comparison of the spanwise distribution of circulation with computed values is shown. The data shows the roll-up of the velocity field around the tip into a tip vortex and the flow patterns on planes above and below the blade. Predicted results are seen to be in good agreement with the measured values at inboard stations, but more work is seen to be necessary for better prediction of the flow around the tip. Sources of possible error in the measurement are discussed.

OBSERVATIONS ON COMPRESSIVE LOCAL BUCKLING. POSTBUCKLING AND CRIPPLING OF GRAPHITE-EPOXY AIRFRAME STRUCTURE

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EXTENDED ABSTRACT

The use of composite materials in primary airframe structure has resulted in weight savings, which directly translate into performance enhancement, and enhanced durability due to relative freedom from fatigue and corrosion. Semi-monocoque, stiffened construction is often utilized. The distinguishing features are substantial reductions in the number of fasteners used and widespread use of co-curing, co-bonding and secondary bonding to attach stiffening elements to skin. In relative lightly loaded portions of an airframe, additional weight savings can be achieved in some cases by permitting members to operate in a postbuckled condition below limit load.

The increased weight savings achieved in this manner are particularly important to overall system performance in V/STOL aircraft. Weight may be translated into increased payload, extended range or downsizing of the vehicle.

In order to design postbuckled structure on a rational basis, it must be possible to reliably predict the following behavioral characteristics:

1. Onset of local buckling;

2. Postbuckling behavior, including membrane load redistribution after buckling; and

3. Crippling or failure, including the originating site and mode.

An experimental and theoretical program is in progress which is directed toward developing the technology needed for these predictions.

DESIGN ANALYSIS METHODOLOGY FOR COMPOSITE ROTOR BLADES

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ABSTRACT

Composite material systems are now the primary materials for helicopter rotor system applications. Bearingless rotor designs proposed for the LHX helicopter are an example. In addition to reduced weight and increased fatigue life, these materials provide designs with fewer parts which means increased service life and improved maintainability. Also, in terms of manufacturing, it is possible to achieve more general aerodynamic shapes including flapwise variation in planform, section and thickness.

The aeroelastic environment in which rotor blades operate consists of inertial, aerodynamic and elastic loadings. Because of the directional nature of the composite materials, it is possible to construct rotor blades with different ply orientations and hybrid combinations of materials exhibiting coupling between various elastic modes of deformation. For example, plies with fiber orientations placed appropriately in the upper and lower portions of the blade can produce elastic coupling between twist and flapwise bending or between twist and extension. This provides a potential for improving the performance of a blade through elastic tailoring of the primary load-bearing structure.

A working definition of elastic tailoring is the use of structural concept, fiber orientation, ply stacking sequence and a blend of materials to achieve specific performance goals. In the design process, materials and dimensions are selected to yield specific elastic response characteristics which permit the goals to be achieved. Common choices for goals for the application of elastic tailoring are the creation of favorable deformations, often for the purpose of preventing or controlling aeroelastic phenomena or vibration, and damage tolerance.

Current design practice for composite rotor blades is to treat them similar to metal designs. The only distinguishing feature is that the effective extensional modulus is not related to the shear modulus. This approach, therefore, does not permit description of general composite layups and cannot be applied if unusual ply layups are introduced in order to create favorable elastic coupling for enhanced performance.

A composite rotor blade structural model and corresponding theory are presented herein which are created to accurately, but simply, characterize response. Simplicity is achieved by considering a primary structural box or single closed-cell spar, the primary load bearing element, as a thin walled beam made of an arbitrary composite layup. The full potential is included to account for the influences of elastic tailoring. In addition, two nonclassical influences - transverse shear deformation and torsion-related warping - are included in the theory as these effects are far more pronounced for laminated composite materials than for monolithic metallic materials.

NONLINEAR DEFORMATION OF ROTATING BEAMS - AN ALTERNATE METHOD OF FORMULATON

V.R.P. Jonnalagadda
Graduate Research Assistant
and
G. Alvin Pierce
Professor
Georgia Institute of Technology
Atlanta, Georgia

ABSTRACT

The dynamic response and aeroelastic stability of helicopter rotor blades can be determined by first formulating the blade equations of motion. The procedure in deriving the blade equations often includes the use of a transformation matrix relating the undeformed and the deformed coordinate systems of the blade. The customary practice is to treat the blade as a long slender beam undergoing combined bending and torsion for which the transformation matrix is derived using Euler angles. The question of which rotational sequence to use is left to choice. Thus, use of different rotational sequences results in different definitions for the torsional variable. In this note, a procedure is demonstrated which eliminates the use of Euler angles and thus for the proposed definition of the torisional variable, the resulting transformation matrix is unique.

Effect of Cyclic Pitch Variations on Hingeless Rotor Blade Stability

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The dynamic response and aeroelastic stability of helicopter rotor blades can be determined by first formulating the blae equations of motion. In the literature, rotor blade equations have been derived by adding the blade root pitch setting to the pretwist present in the blade and the torsional variable as defined about the deformed elastic axis of the blade (references 1, 2, and 3). Thus, any collective and cyclic pitch variations near the blade root were treated to be occuring about the deformed elastic axis all along the blade. Such a treatment may not accurately represent the effect of inertial coupling terms resulting from the fact that the pitch variations occur about the undeformed feathering axis of the blade.

In the present study, an additional transformation through the blade root pitch angle is carried out so that the collective and cyclic pitch variations are represented about the undeformed feathering axis of the blade. The blade equations of motion are derived using Hamilton's variational principle. The aerodynamic forces are obtained using a quasi-steady approximation of two-dimensional, unsteady airfoil theory. An ordering scheme type of approximation which is consistent with slender beam theory is used to systematically eliminate higher order terms. The resulting blade equations are found to contain explicit coupling terms involving time derivatives of the blade root pitch angle such as v , w , v , w , etc.

To evaluate the effect of these so called "control terms" on the linear stability of the blade, numerical studies have been carried out for typical hingeless rotor blade configurations. First, the spatial variable in the blade equations is eliminated using Galerkin's technique wherein the displacement variables are represented in terms of uncoupled nonrotating cantilever modes. The resulting modal equations of the blade are rewritten in first order state variable form. A propulsive trim procedure which simulates actual forward flight conditions is used to arrive at the trim values for the control setting (reference 4). Using the homogeneous part of the linear set modal equations, the Floquet transtition matrix is obtained through numerical integration. The stability of the linear system is predicted from the characteristic exponents of the Floquet transition matrix.

ELASTIC FUSELAGE MODES AND HIGHER HARMONIC CONTROL IN THE COUPLED ROTOR/AIRFRAME VIBRATION ANALYSIS

by

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ABSTRACT

A coupled rotor/airframe vibration analysis model has been used to study variations in the higher harmonic control vector and vibration levels of the fuselage. The differences between minimization of the hub forces and the acceleration at a selected fuselage location have been discussed. Also the effects of nonideal conditions in the implementation of higher harmonic control and the resulting residual vibration levels in the fuselage have been discussed. The coupled rotor/airframe vibration model is based on an assumed mode rotor model, a finite element or an assumed mode fuselage model and impedance matching techniques.

PROGRESS REPORT

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2. **PERIOD COVERED BY REPORT**: 1 JANUARY - 30 JUNE 1986

3. **TITLE OF GRANT NUMBER**: A CENTER OF EXCELLENCE FOR ROTARY WING AIRCRAFT TECHNOLOGY

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5. **NAME OF INSTITUTION**: GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF AEROSPACE ENGINEERING

6. **AUTHOR(S) OF REPORT**: R.B. Gray, J.I. Craig, S.V. Hanagud, J.J. Harper, S.S. Klein, N.M. Komerath, S.G. Lekoudis, H.M. McMahon, S.A. Meyer, G.A. Pierce, N.L. Sankar, L.W. Rehfield, J.C. Wu

7. **LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES**:

Publications:

1. Rehfield, L.W., and A.D. Reddy, "Observation's on Compressive Local Buckling, Postbuckling and Crippling of Graphite/Epoxy Airframe Structure," AIAA Paper 86-0923, Proceedings of the 27th AIAA SDM Conference, San Antonio, TX, 19-21 May 1986, pp. 301-306.

2. Bauchau, O.A., B.C. Coffenberry, and L.W. Rehfield, "Composite Box Beam Analysis: Theory and Experiments," submitted to Journal of Reinforced Plastics and Composites.

3. Reddy, A.D. and L.W. Rehfield, "Postbuckling and Crippling Behavior of Graphite/Epoxy Thin-Walled Airframe Members," accepted for publication in the Journal of the American Helicopter Society.

4. Wu, J.C., C.W. Wang, and N.L. Sankar, "Dynamic Stall of Oscillating Airfoils," Proceedings of the 42nd Annual American Helicopter Society Forum, June 2-4, 1986.

5. Sankar, N.L., B.E. Wake, and S.G. Lekoudis, "Solution of the Unsteady Euler Equations for Fixed and Rotor Wing Configurations," Journal of Aircraft, Vol. 23, April 1986, pp. 283-289.

6. Wake, B.E., N.L. Sankar, and S.G. Lekoudis, "Computation of Rotor Blade Flows Using the Euler Equations," Journal of Aircraft, Vol. 23, No. 7, July 1986, pp. 582-588.

7. Sankar, N.L., and C. Tung, "Euler Calculations for Rotor Configurations in Unsteady Forward Flight," Proceedings of the 42nd Annual Forum of the American Helicopter Society, June 2-4, 1986.

8. Wake, B.E., and N.L. Sankar, "Solutions of the Navier-Stokes Equations for the Flow About a Rotor Blade," AHS Southwest Region National Specialists' Meeting, Ft. Worth, Texas, February 25-27, 1987.

9. Hanagud, S., M. Meyyappa, and J.I. Craig, "Basic Research in Structural Dynamic System Identification," 42nd Annual Forum of the American Helicopter Society, Washington, D.C., June 2-4, 1986.

10. Chattopadhyay, Aditi, S.V. Hanagud, and C.V. Smith, Jr., "Minimum Weight Design of a Structure with Dynamic Constraints and a Coupling of Bending and Torsion," AIAA SDM Meeting, San Antonio, TX, May 1986.

11. Hanagud, S., M. Meyyappa, S. Sarkar, and J.I. Craig, "A Coupled Rotor/Airframe Vibration Model with Higher Harmonic Control Effects," Proceedings of the 42nd Annual Forum of the American Helicopter Society, June 2-4, 1986.

12. Hanagud, S.V., Aditi Chattopadhyay, Jin Zhang, and Y. Wang, "Mechanism of Energy Absorption via Buckling: An Analytical Study," Crashworthy Design Specialists' Meeting, April 1986.

Presentations:

1-4. Rehfield, L.W., "An Overview of Research on Composite Airframe and Rotor System Structures," United Technologies Symposium, Georgia Institute of Technology, February 25, 1986.

Also presented at:

- Lockheed-Georgia Company, March 4, 1986
- Rolls-Royce, Inc., March 12, 1986
- University of Delaware, April 22, 1986

5. Rehfield, L.W., "Design Issues for Modern Helicopter Rotor System Structures," Memorial Lecture to Honor James Alvin Stricklin, Texas A and M University, College Station, TX, May 22, 1986.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Principal Investigator: R.B. Gray

Faculty: J.I. Craig, A.L. Ducoffe, S.V. Hanagud, N. Komerath, S.G. Lekoudis, H.M. McMahon, G.A. Pierce, L.W. Rehfield, N.L. Sankar & J.C. Wu

Research Engineers: S. Klein, R. Latham, S.A. Meyer

Research Associates: J. Caudell & H. Meyer

Post Doctors: V.R. Anand, A. Chattopadhyay, M. Meyyappa, & C. Wang

Fellows: Ph.D.: Albert G. Brand, Dimitrios N. Mavris, Thomas L. Thompson, Dana J. Taylor, Brian Wake

M.S.: Chris Fouts, Jeff W. Harding, M.W. Heiges, Mark Wasikowski

Graduate Research Assistants: Ph.D.: N.S. Abhyankar, R. Chander, P. Cheng, W.K. Daniel, M. Hashemi-Kia, V.M. Kaladi, Y.K. Kim, O.J. Kwon, S.G. Liou, Mike T. Patterson, S. Sarkar, P. Sriram, W. Tang, I. Tuncer, C.C. Won, Y.K. Yillicki, W. Zhou

M.S.: B. Glass, R. Jolly, J.L. Kemnitz, L.S. Mayer, H.E. Mersinoglou, R. Srivastava

CONTRIBUTED TO PROJECT BUT WERE NOT SUPPORTED

Faculty: J.J. Harper, D.P. Schrage, D.A. Peters

M.S. Students: M. Obal

B.S. Students: T. Moore and D. Ngo

DEGREES AWARDED (THIS REPORTING PERIOD)

NAME	DEGREE-DATE	PRESENT AFFILIATION
CPT D. Jenkins	MS - June 1986	U.S. Army AVSCOM
T. Moore	BS - June 1986	M.S. Program Georgia Tech
D. Ngo	BS - June 1986	M.S. Program RPI
M. Pollack	BS - June 1986	Sikorsky Aircraft

DEGREES AWARDED (CUMULATIVE)

NAME	DEGREE-DATE	PRESENT AFFILIATION
N.S. Abhyankar	MS - Dec 1981	PhD Program Georgia Tech
V.R. Anand	PhD- Dec 1982	Georgia Tech
A.G. Brand	MS - Sept 1985	PhD Program Georgia Tech
T. Boyd	MS - Sept 1983	US Air Force
C. Boyette	MS - Dec 1983	McDonnell Douglas
C. Brevoort	MS - Sept 1983	Lockheed Georgia
CPT C.N. Cardinal	MS - June 1984	US Army
H.P. Chen	PhD- Dec 1983	Georgia Tech
MAJ M. Clifford	MS - Dec 1982	US Army
J.E. Corban	*BS - June 1983	McDonnell Douglas
P.L. Elliot, III	*BS - June 1983	Boeing Vertol Co.
K. Engelhardt	MS - Sept 1983	McDonnell Douglas
P.J. Georges	MS - Sept 1984	ONERA
C. Grimmell	MS - June 1984	General Dynamics
B.A. Gustavson	MS - Sept 1982	Kaman Aerospace
MAJ W. J. Hatch	MS - June 1984	US Army
J.A. Humphries	MS - June 1984	US Air Force
CPT D. Jenkins	MS - June 1986	US Army AVSCOM
V.R.P. Jonnalagadda	MS - Sept 1983	Georgia Tech
	PhD- Sept 1985	Georgia Tech
V.M. Kaladi	MS - Sept 1985	PhD Program Georgia Tech
Y.K. Kim	MS - Sept 1985	PhD Program Georgia Tech
S.G. Liou	MS - Sept 1985	PhD Program Georgia Tech
D. Mavris	MS - Sept 1985	PhD Program Georgia Tech
CPT W. McArthur	MS - March 1983	US Army
T. Moore	*BS - June 1986	M.S. Program Georgia Tech
D. Ngo	*BS - June 1986	M.S. Program RPI
P. Oliver	MS - June 1985	McDonnell Douglas
D. O'Neil	MS - Sept 1984	McDonnell Douglas
T. Parham	MS - Sept 1983	Bell Helicopter Textron
M. Pollack	*BS - June 1986	Sikorsky Aircraft
G. Power	MS - Sept 1983	United Technologies Research Center
D. Pritchard	MS - Sept 1984	PhD Program Georgia Tech Graduate Co-op McDonnell Douglas
J. Rogers	MS - Sept 1983	General Dynamics
S. Sparks	MS - Sept 1983	United Technologies Research Center
D.J. Taylor	MS - Sept 1984	PhD Program Georgia Tech
T. Thompson	MS - Sept 1983	PhD Program Georgia Tech
R.R. Tipton	MS - Aug 1983	McDonnell Douglas
B. Wake	MS - Sept 1984	PhD Program Georgia Tech
T. Wey	PhD- Dec 1983	Lockheed-EMSCO, Inc.

*Completed one or more helicopter related courses.

RESEARCH TASKS

I. Aerodynamics

Task 1. Experimental Studies for Tip Vortex Core Modeling
R.B. Gray, N.M. Komerath, T.L. Thompson, J.L. Kemnitz, O. Kwon

The objectives of this task are to develop a capability for measuring the flow field near the tip and in the wake of a hovering helicopter model rotor using a laser velocimeter and to use the data to guide the development of a tip vortex core model for use in free wake analyses for blade loading predictions. The longer term objectives are to develop a hovering vortex wake analysis which is not as dependent on empirical parameters for describing the tip vortex geometry and to investigate the extension of the vortex wake analysis to low-speed forward flight.

During the last reporting period, an extensive set of measurements has been completed in the 9-foot hover facility. Data has been obtained on the velocity profile in the core of the tip vortex. For this purpose, a new remote-aligned off-axis scatter receiving system had to be invented. This device was built during the last six months, tested, calibrated, and used successfully. This has enabled data of excellent quality to be obtained using seed particles small enough to follow the highly accelerated flow in the vortex core. These particles are too small to be sensed by conventional backscatter receiving systems at the long focal lengths used in this facility. Forward scatter systems mechanically linked to the transmitting optics are impractical in this facility. Thus the development of this device represents a crucial step in making the measurement of the vortex core velocity profiles feasible, and it has had the desired effect.

A program of flow visualization was also undertaken during the past six months to check the vortex trajectory data obtained before, and to settle the question of "vortex jitter". A laser sheet strobed in phase with the rotor was used to illuminate thin slices of the seeded flowfield. Intersections of up to three turns of the vortex trajectory with the sheet could be seen and photographed. Analysis of the data showed that the vortex trajectory was very steady in the first 180 degrees of vortex age, so that near wake LDV measurements are not affected. Beyond 180 degrees, unsteadiness increases, and is quite noticeable at 360 degrees. The size of the vortex core could also be clearly identified as the region devoid of seed particles. The size of this region was seen to increase with vortex age, and its edges became less clearly defined, as expected. The vortex trajectory measured by this technique confirmed previous LDV data. This technique makes precise visualization of the vortex core possible even at low tip Mach numbers, where density gradients in the core are too weak to permit shadowgraphy. It also does not require the placement of intrusive smoke jets at the tip, though low-speed clouds of mineral oil droplets do make the vortex more visible. This technique will next be tried in the forward flight facility on a two-bladed rotor, and then in the 16-foot facility on the 4-bladed MDHC HARP rotor.

An effort to quantify and correct errors in LDV data acquired in accelerating flows with larger seed particles is in progress.

Velocities predicted in the inflow region using the code of Wey and Gray show excellent agreement with the LDV data. In the wake, agreement is good except during passage of the tip vortex, where differences are significant.

Task 2. Modification of Blade Tip Loading to Improve Hovering Figure of Merit
R.B. Gray & T. Thompson

Measured pressure distributions on the tip of a hovering model rotor blade show a low pressure region which is associated with the roll-up and rearward sweep of the tip vortex over the trailing 50% for the blade upper surface. This low pressure region near the trailing edge contributes significantly to the section pressure drag and hence to the rotor power required. The objective of this task is to explore the possibilities of improving performance by modifying the tip pressure distribution.

This research task has been completed and a final report will be prepared.

Task 3. The Prediction of Flow Around Blade Tips
R.B. Gray, N.L. Sankar, B.E. Wake

The objective of this task is to develop a procedure to accurately predict the flow field, and hence the airloads in the vicinity of the tip of a rotor blade. This requires a correct prediction of the vortex formation and roll up processes and the strength and location of any shocks.

The three-dimensional, compressible, unsteady Navier-Stokes solver was calibrated during the reporting period for laminar and turbulent flows. A NACA 0012 rotor blade of rectangular planform in hover was chosen for detailed study. The blade is untwisted and has an aspect ratio of 6. The effect of the tip vortices that lie outside the computational domain was accounted for as a simple correction to the blade collective pitch angle. The steady surface pressure distributions at a number of span stations have been compared with the experimental results obtained by Caradonna and his co-workers at the NASA Ames Research Center. Reasonably good agreement was observed everywhere on the rotor, except at the immediate vicinity of the rotor tip. Here the global cyclic pitch correction approach does not account for the rapid variations in the inflow associated with the tip vortices which lie outside the computational domain. Effort is now underway to improve the correlation near the tip region, using a radial induced velocity distribution obtained from the CAMRAD code.

A set of unsteady, turbulent viscous flow calculations were carried out for a non-lifting NACA 0012 rotor in forward flight. The tip Mach number and the advance ratio were 0.8 and 0.2 for this case. The eddy viscosity was modeled with a two layer Baldwin-Lomax model. The surface pressure distributions in the tip region are in good agreement with the experimental data recently obtained by Schmitz et.al.

The findings of the above research have been included in an abstract submitted to the AHS Specialists' Meeting, to be held in Texas early next year.

Task 4. Studies of Unsteady Rotor Aerodynamics
J. C. Wu, N.L. Sankar, C. Wang, C. Fouts, J.R. Jolly, M.T. Patterson, R. Srivastava, W. Tang, I. Tuncer

The purpose of this task is to develop theoretical and computational tools for the prediction of the unsteady airloads on modern rotor blades in hover and in forward flight.

The 2-D, incompressible Zonal solver was validated for a number of static and dynamic stall applications. Comparisons were done with the experimental studies of Werle at ONERA and with the numerical investigations of other researchers. These comparisons indicate that the Zonal solver is capable of accurately predicting the events leading to the dynamic stall, and the post stall flow recovery. The findings of the research during this period have been presented at the AHS 42nd Annual Forum.

The 2-D compressible Navier-Stokes solver, which in the past has been applied to weak BVI interactions, was extended to strong blade-vortex interaction applications. Cases were studied in which a vortex approaches the airfoil, collides with it and breaks into several smaller vortices. These smaller vortices are then carried away by the fluid both above and below the airfoil. To our knowledge this is the first time such calculations have been done using a compressible flow solver. In the past, all the transonic flow solvers (Full Potential, Transonic Small Disturbance and Thin Layer Navier-Stokes codes) have treated the passing vortex as a point vortex, with a small viscous core. The details of the vortex core, the deformation of the vortex into several smaller vortices, etc., have not been studied using these solvers. Thus, the present extension is considered a useful contribution to the study of close blade-vortex interactions.

At the request of Bob Flemming of Sikorsky, and J. Shaw of NASA Lewis Research Center, the 2-D compressible Navier-Stokes solver was used to predict the performance of airfoils with a simulated leading edge ice shape. The findings were compared with the results from a wind tunnel test done at the Ohio State University. These findings are to be presented at a Workshop held at the NASA Lewis Research Center July 17-18, 1986.

Task 5. Studies of Airframe Flowfield in Forward Flight
H.M. McMahon, N.M. Komerath, A. Brand, D. Mavris, S. Liou, H. Mersinoglou

The long-term objective of this task is the development and validation of a reliable technique for predicting the coupling between rotor and airframe aerodynamics. The short term goals are to provide a data base for developing and assessing analytical models, to assess existing analytical models, and to investigate the flow features important in rotor-airframe aerodynamics.

Following the calibration of the wind tunnel force balance, a three degree of freedom computer-controlled traversing system has been installed in the test section of the 7 x 9 - foot wind tunnel. Both hot-wire and total pressure probes have been used to make measurements in and around the rotor wake. It has been found that by using a total pressure Kiel probe it is possible to define the time-averaged geometry of the rotor wake with satisfactory accuracy and repeatability. Data have been taken at several advance ratios in order to determine the wake shape in the absence of the airframe. The fuselage model was then installed and the measurements are now being repeated.

The turbulent intensity of the freestream flow in the test section was measured with the hot wire and found to be acceptably low (0.4%). This hot wire will be used to make benchmark comparison measurements with the LDV when the LDV is moved to the wind tunnel about August 1, 1986. In preparation for these tests, the steel protection plates on the test section have been modified to allow a larger field of view around the rotor tip path plane. Also, plans have been developed to modify the sidewalls of the test section in order to allow the installation of forward scattering optics and accessories and to further enlarge the field of view of the LDV.

Regarding the analytical effort, the AMI code (VSAERO) has been run for several simple test cases as a diagnostic tool to examine certain subroutines. These test cases have included the two-dimensional flow around a cylinder, a uniform jet in a freestream, and several cases of an isolated rotor in forward flight. Comparisons of these test results with analytical solutions have been informative and have led to the correction of several errors in our version of the VSAERO code. A final comparison of the VSAERO predictions with the experimental results is now being made. Simultaneously, a literature search is underway to find and develop a new rotor code that will be used with the VSAERO body panel code and the supporting body/rotor interaction subroutines in order to improve the agreement between theory and experiment.

II. Structures

Task 1. Structural Dynamic System Identification

S.V. Hanagud, J.I. Craig, N.S. Abhyankar, A. Chattopadhyay, M. Meyyappa, Y. Cheng, M. Obal, S. Sarkar, O.J. Kwon, Y.K. Yillicki

The purpose of this task is to develop an approach to advance the state of the art in airframe structural dynamic modeling. Development of applicable system identification techniques - the mathematical model of the system of interest - and improved physical models are the basis for this research.

A significant amount of progress has been made in developing techniques to identify structural dynamic systems with (a) general damping matrices (b) aerodynamic contribution and (c) nonsymmetry. Techniques for systems with general damping matrices have been validated by using tests on a fullscale tailboom. The developed techniques are based on the equation error approach.

In early developments the technique was capable of identifying systems that have relatively small degrees of freedom and all measured modes. The current developments can accommodate relatively large degrees of freedom and measured data containing only a few modes in relation to the degrees of freedom.

Preliminary work has been done in using system identification techniques in higher harmonic control. In particular the benefits of using minimum deviation filters have been explored.

In preparation of developing techniques for identifying distributed parameter systems, techniques for numerically integrating the partial differential equation of the rotor blade aeromechanical system are being developed. Progress has also been made in the area of structural dynamic scale model development by using identification techniques. A scale model has been developed for a full scale tailboom that is at present located in the structural dynamics laboratory. Tests are planned on the model and the full scale structure.

Many of the identification techniques use several optimization methods. In this area of research work, development algorithms to couple the identification and optimization procedures are being explored. Such an algorithm is useful in design modifications with the availability of experimental or flight test results.

The state of the art of structural dynamic system identification has been reviewed. Three lectures in different areas of the reviews were presented at (a) AHS Forum, (b) Bisplinghoff Memorial Symposium, and (c) Southeastern Conference of Theoretical and Applied Mechanics. Furthermore, efforts have been made to understand the implementation and user procedures for GRASP. The purpose is to explore the use of GRASP in identification techniques.

Task 2. Crashworthy Characteristics of Composite Rotorcraft Structures
S.V. Hanagud, R. Chander, B. Glass, L.S. Mayer, P. Sriram, W. Zhou

The objective of this task is to conduct basic research to develop improved techniques and procedure for designing crashworthy composite structures for rotorcraft. This objective includes the development of testing techniques and optimization of the crashworthy designs under the constraints of weight restrictions, cost and performance requirements.

Preliminary work has been initiated in the subject of the analysis of mechanisms of energy absorption in graphite-epoxy composites. This will involve the analysis of energy absorption by means of brittle fractures. Discussions were held with Mr. G. Farley of U.S. Army Aerostructures Directorate, NASA Langley Research Center, Hampton, Virginia. Some discussions have also been held with Mr. V. Berry, Bell Helicopters, Mr. J. Cronkhite of Bell Helicopters, Mr. J.K. Sen of McDonnell Douglas Helicopters, and Mr. Kindervater of DFVLR. Preliminary tests have been conducted on selected graphite-epoxy curved web specimens. Information on the manufacturing process for tubes has been obtained. Theoretical analysis by using three dimensional finite element technique is in progress. Several brittle fracture initiation criteria are being evaluated at present.

During the early part of this reporting period theoretical analysis of energy absorption of Kevlar-epoxy curved web specimens by a post buckling mechanism has been studied. Modification of a crash analysis program such as KRASH to use analytically generated low deflection curves are being studied. In order to calculate forces and the resulting stresses on different parts of a human body during simulated crashes, a human body model is being analyzed along with KRASH. An improved human body model as a multi-linked body system is being investigated. Kane's dynamical equations are being used to generate the improved model.

Also, using KRASH and tests, correlation studies on state and dynamical analysis/tests have been evaluated for specific cases.

By the use of digital optical speckle techniques, strain and displacement fields during (a) the brittle fracture of graphite-epoxy composites and (b) post buckling of Kevlar-epoxy specimens are being studied.

An AHS Crashworthy Design Subcommittee has been formed as a subcommittee of the AHS Structures and Material Committee.

Task 3. Concepts for Stability Critical Airframe Structures
A.D. Reddy & L.W. Rehfield, W.K. Daniel

This task is concerned with crippling and postcrippling behavior of thin walled graphite/epoxy composite airframe members in axial compression. The main objectives are to i) generate an experimental data base on the crippling and postcrippling behavior, ii) develop simple analytical methods to predict these behavior, and iii) provide better insight into the failure processes for this type of structure.

A number of important investigations have been completed which provide significant findings. Emphasis has been given to experiments in this period, which has been facilitated by Dr. Ambur Reddy acting as a consultant. An experimental measure of nonlinearity in the postbuckling regime has been developed and determined for each of the five-ply layups in the Sikorsky-built I-beams. Some layups display noticeable nonlinearity, others practically none.

Hysteresis experiments have been conducted on the I-beams that exhibited some nonlinear behavior. Permanent strains were found to be negligible.

Use of mode I suppression to alter the crippling behavior of the flanges has been successfully applied. High speed films show that delamination is suppressed and that compressive laminate failure was the newly-created failure mode.

Task 4. Composite Rotor Blade Modeling
L. W. Rehfield

Further coordination of the rotor blade work with the Aerostructures Directorate at Langley Research Center has been achieved. Some new findings are extremely significant. While attempting to tailor a rotor blade configuration to achieve high extention-twist elastic coupling, it is found that a new form of coupling, previously unexplored shear force-moment coupling, is created as a natural byproduct. This has a very significant effect on bending response and is receiving our attention now.

III. Aeroelasticity

Task 1. Helicopter Vibration Suppression Techniques
G.A. Pierce, V. Anand, V.M. Kaladi, Y.K. Kim, D.J. Taylor

This program is intended to develop and validate comprehensive vibratory loads analyses for the evaluation of vibration suppression techniques. The loads analyses will be applicable to nonuniform multibladed systems with various hub constraints. Special emphasis is placed on blade structural dynamics and unsteady blade aerodynamics.

During this reporting period, the previously developed blade response analysis which incorporated a unique undeformed/deformed blade coordinate transformation was completely reprogrammed to analyze nonuniform blade configurations. This "comprehensive analysis" can be applied to rotors in hover or forward flight conditions and incorporates an automated trim procedure. The program can be used to determine stability characteristics or dynamic response in normal operation or in the presence of external disturbances. Hub configurations which the analysis can currently treat include hingeless and articulated designs. Efforts have been initiated to extend the applicability of the analysis to teetering and bearingless configurations.

The results of the preliminary study of bearingless blade restraints as reported in the last progress report are being applied to the general aeroelastic analysis described above. The first treatment of the bearingless configuration will presume that the transverse inertial loading of the flexural unit can be neglected with respect to the elastic loading. This technique has proven to yield quite good results with respect to the great simplification which it affords. The second treatment of the bearingless case will be the matching of two beams as a nonhomogeneous boundary value problem. This method has been demonstrated as being a very accurate yet versatile simulation of bearingless designs.

Work has continued on the development of a generalized "harmonic analysis" of multibladed rotors with nonuniform blades. Although this technique is restricted in application to problems of harmonic dynamic response it is computationally very efficient. As a result it will be ideally suited for the design analysis of higher harmonic vibration suppression systems.

During the next reporting period both the comprehensive and harmonic analyses will be applied to the Aeroelastically Conformable Rotor (ACR) model which is currently installed in the Aeroelastic Rotor Test Chamber. The results obtained from these programs will be used to design a stability and response test program for the ACR rotor. Data from these programs will also be correlated with measurements taken during the tests.

FACILITIES/EQUIPMENT

I. Laser Doppler Velocimeter (LDV) Data Acquisition System

N.M. Komerath, R.B. Gray, H.M. McMahon

The four-beam, two color Laser Doppler Velocimeter (LDV) consists of a five-watt Argon Ion Laser, modular optics, a three-axis traversing system, and two counter-type signal processors directly interfaced into the memory of a dedicated HP1000 computer system. Two orthogonal components of flow velocity can be measured simultaneously and nonintrusively with a spatial resolution of 0.1 millimeters from a distance of up to 2200 mm. Frequency shifting on both channels enables measurement of the velocity vector in recirculating flows and a field stop system enables measurements close to solid surfaces.

During the last reporting period, the system was used very heavily in flow visualization and velocity measurements in the 9-foot hover facility. The laser and traverse system were used in creating light sheets of varying divergence to illuminate precisely known cross-sections of the rotor wake. The beam was strobed using synchronous motors at the rotor frequency, and light scattered from the seeded flow was used to visualize up to 1080 degrees of vortex core geometry. Quantitative measures of vortex core size, trajectory, and unsteadiness were obtained. This technique is seen to be well suited to the visualization of vortex geometry at low tip Mach numbers.

The remotely-aligned off-axis scatter receiving system which was designed during the previous reporting period was completed, tested, and calibrated. It has proved to be a success, and has seen extensive use during this period in performing velocity measurements in the vortex core.

Attempts to measure seed particle settling rates in order to quantify particle size have so far not succeeded since the particle settling velocities are extremely low, and a suitably quiescent environment has not yet been created. Currently efforts are in progress to develop methods of quantifying and correcting for particle lag error. When these are developed, the particle sizing effort will be taken up again, though it has to take a low priority in view of the heavy routine use of the LDV.

The core measurements in the 9-foot facility completed, the LDV is being moved during July to the Low Speed Wind Tunnel.

II. Nine-Foot Static Thrust Facility

R.B. Gray

The facility provides a laboratory-controlled environment for testing model helicopter rotors up to 4.5 feet in diameter in hovering flight. The LDV system described above is being used for data acquisition for Aerodynamics Task 1. The facility has also been used for Aerodynamics Task 2. The updating of this facility has included factory reconditioning of the mercury slip-ring assembly, which is now in progress.

III. Structural Dynamic System Identification Facility

S.V. Hanagud, J.I. Craig

This laboratory is developed to measure, record, process, and analyze structural dynamic data for laboratory model tests and field tests. The multi-channel time series and structural dynamic analyzer allows acquisition of data from one to eight channels simultaneously with the capability to expand to sixteen. The analysis software may run on the dedicated computer system or is portable to another system.

IV. Transient Dynamic Stress Analysis Facility

S.V. Hanagud, J.I. Craig

This facility is for the study of the dynamic behavior of structural components and assemblies under typical crash-induced loading situations for helicopters. The design of the facility involves a drop-test fixture for producing dynamic compressive loading of various metallic and composite test articles. A variety of waveform recorders acquire data during investigation of crashworthy characteristics of rotorcraft structures, particularly composite structures.

V. Seven-by-Nine Foot Forward Flight Facility

J.J. Harper, H.M. McMahon, S.S. Klein

The closed low speed wind tunnel is the forward flight facility with a seven-by-nine foot test section. The design and installation of a powered model rotor system, fairings, floor, ceiling and honeycomb provide a total laboratory environment. The rotor system is mounted from the test section ceiling and fuselage models are mounted on a force balance sting. The Laser Doppler Velocimeter, a dedicated computer system and a modern force balance provide for data acquisition. During this reporting period, a three degree of freedom computer controlled transversing system has been installed. Both total pressure and hot-wire probes have been installed and utilized.

VI. Aeroelastic Rotor Test Chamber

G.A. Pierce, S.S. Klein, M. Hashemi-Kia

The primary purpose of this facility is to permit scaled testing of rotor systems. Such tests are to be concerned with steady and unsteady aerodynamic phenomena, structural dynamic response behavior and aeroelastic stability characteristics. Model rotor systems of up to ten feet in diameter can be accommodated.

Up to 40 channels of model-mounted transducer signals can be amplified by a rotating differential-amplifier package prior to being transmitted to the control room via the 52-channel slip-ring assembly. These signals plus others can be subsequently amplified by a bank of 48 NEFF amplifiers. Of these amplifier outputs 32 (previously 16) channels can be processed on-line by an analog-to-digital converter for transmission to the HP1000 A700 computer system. The HP1000 system has been expanded from 1 to 4 MB of memory and from 64 to 200 MB of disk storage. In addition to the 32 channels of data input to the HP1000 system, another 16 channels can be received by a Genrad 2515 CAT system. This 16-channel programmable system is capable of executing numerous spectural analysis operations on the incoming data.

During this reporting period, a dynamic calibration was performed on the three channels of hydraulic actuators. This calibration entailed sending known harmonic signals from the HP 1000-A700 computer system through the digital -to-analog converter to each of the three actuator controllers. As the actuators responded to these controlled inputs the signals from the linear variable differential transformers (LVDT) which are built into each actuator were sent back to the computer via the analog-to-digital converter. These LVDT signals are a direct measure of the actuator displacement and were related to the physical displacement by a prior static calibration with a dial gage. Correlation of the output and input signals to the computer yielded the desired calibration between computer control signals and physical displacement of the actuators. This calibration was conducted over the entire range of actuator displacement at five frequencies from ten to fifty Hertz (one to five per Rev).

As with the calibration of any new and innovative system, numerous problems were encountered which had to be solved. Most of these were concerned with required electronic modifications and adjustments to the actuator controllers. One significant mechanical problem arose when one of the three high high pressure (3000 psi) hydraulic accumulators lost a seal and sprayed hydraulic fluid over the work area. To prevent future equipment damage from a recurrence of such an incident the entire high pressure system of hoses and accumulators have been encased in conduit and sealed containers. In addition to preventing equipment damage, this facility modification should also insure against personnel injury in the event of a high pressure hose failure.

To relate computer output control signals to associated blade pitch angle orientation it was necessary to conduct a kinematic analysis of the complete linkage mechanism from the actuators through the swashplate and pitch links to the blades. These kinematical results together with the actuator calibrations discussed above provide sufficient computer intelligence to permit direct control of collective, longitudinal cyclic and lateral cyclic pitch inputs to the rotor. With the completion of these calibrations it is now possible to program desired pitch variations for dynamic response testing, and to also incorporate a harmonic controller into the system.

UPDATED AND NEW COURSE DEVELOPMENT

The updating of courses and the development of new courses that were listed in the contract have been completed. All courses have been taught at least once except for one updated course, Advanced Aeroelasticity II, which is offered on demand. The Unsteady Aerodynamics course was initially offered during the spring of 1986. A summary of the status of these courses is shown in Table I. The number indicating the students enrolled includes students in all disciplines in the A.E. Graduate Program. A measure of the interest in the Rotorcraft Program is indicated by the enrollment in the Rotorcraft Design course although the number given includes students not supported by the Center.

The rotor theory courses that were in existence when the Center was established continue to be taught. A summary of the enrollments is also attached as Table II. Again, the number of graduate students indicates the interest in the Rotorcraft Program and includes students who are self supported and supported by other means. The Introduction to Propellor and Rotor Theory course attracts a good number of undergraduate students, some of which interview and accept with the helicopter companies.

ACADEMIC PROGRAM DEVELOPMENT

Discipline	Course No.	Title	Updtd	New	Status	Instructor
Aerodynamics	4600*	Computational Aerodyn.		X	Sum. 1984 - 19**;Wtr. '85- 9** Wtr. '86-13**	Sankar Wu/Wang
	6012*	Viscous Flow III		X	Sum. 1983 - 7**;Sum. '84-20** Sum. 1985 - 11**	Lekoudis/ Strahle
	6022	Adv. Compress. Flow II	X		Spr. 1983 - 9**;Spr. '85-11** Spr. 1984 - 13**;Spr. '86-22**	Lekoudis Sankar
	6402*	Aerody. of Helicop.III		X	Sum. 1984 - 8**;Sum. '85-11**	Gray
	6802*	Num.Fluid Dyn.III		X	Fall 1983 - 11**;Fall '85-12**	Wu
	6810*	Unsteady Aerodynamics		X	Spr. 1986 - 22**	Wu
Aeroelasticity	6030	Adv. Potent. Flow I	X		Fall 1982 - 20**;Fall '83-17** Fall 1984 - 28**;Fall '85-26**	Pierce Pierce
	6031	Adv. Potent. Flow II	X		Wtr. 1983 - 17**;Wtr. '84-19** Wtr. 1985 - 21**;Wtr. '86-21**	Pierce Pierce
	6200	Adv. Aeroelasticity I	X		Spr. 1983 - 8**;Spr. '84-11** Spr. 1985 - 11**;Spr. '86- 6**	Pierce Pierce
	6201	Adv. Aeroelasticity II	X		Offered on demand	Pierce
	6202	Exp. Aeroelasticity	X		Sum. 1983 - 7**;Sum. '84- 7**	Pierce
	8103	Helicopter Dynamics		X	Win. 1986 - 12**	Peters
Design	6350*	Rotorcraft Design I		X	Spr. 1984 - 13**;Wtr. '85- 9** Wtr. '86-14**	Schrage Schrage
	6351*	Rotorcraft Design II		X	Sum. 1984 - 7**;Spr. '85-12** Spr. '86-14**	Schrage

*Proposed Course No. ** No. of Students Enrolled

ACADEMIC PROGRAM DEVELOPMENT(continued)

Discipline	Course No.	Title	Updtd	New	Status	Instructor
Structures	4115*	Intro. Fiber Reinforced Composites		X	Fall 1984 - 20**;Fall '85- 9**	Rehfield
	4116*	Manuf. Compos. Struct.		X	Wtr. 1985 - 23** Wtr. 1986 - 20**	Rehfield Rehfield
	6106*	Finite Def. A/C Struct.		X	Sum. 1985 - 10**	Hanagud
	6132*	Vib. Meas. & Analysis		X	Sum. 1984 - 15**	Craig/Hanagud
	6113*	System Identification		X	Sum. 1984 - 10**	Hanagud

*Proposed Course No.

** No. of Students Enrolled

CENTER OF EXCELLENCE
FOR
ROTARY WING AIRCRAFT TECHNOLOGY

EXISTING COURSES
ENROLLMENT

AE 4400 Introduction to Propeller and Rotor Theory

Summer of 1982:	5 Graduate Students 10 Undergraduate Students
Fall of 1982:	8 Graduate Students 14 Undergraduate Students
Summer of 1983:	1 Graduate Student 6 Undergraduate Students
Fall of 1983:	9 Graduate Students 8 Undergraduate Students
Summer of 1984:	1 Graduate Student 5 Undergraduate Students 1 Special Student
Fall of 1984:	17 Graduate Students 22 Undergraduate Students
Summer of 1985:	3 Graduate Students 13 Undergraduate Students
Fall of 1985:	8 Graduate Students 15 Undergraduate Students

AE 6400 Rotor Aerodynamics I

Winter of 1983:	13 Graduate Students 3 Undergraduate Students
Winter of 1984:	7 Graduate Students 1 Undergraduate Student
Winter of 1985:	14 Graduate Students
Winter of 1986:	16 Graduate Students

AE 6401 Introduction to Helicopter Stability and Control

Spring of 1983:	10 Graduate Students 1 Undergraduate Student
Spring of 1984:	4 Graduate Students 1 Undergraduate Student
Spring of 1985:	14 Graduate Students
Spring of 1986:	16 Graduate Students

Table II

VISITS/COMMUNICATIONS

1. **R.B. Gray**

June 1-6, 1986	42nd American Helicopter Society Forum Washington, DC

2. **S. Hanagud**

January 22-25, 1986	NASA Ames Research Center, Moffett Field, CA
February 5-7, 1986	Bisplinghoff Memorial Symposium, Gainesville, FL
April 27-30, 1986	NASA Langley Research Center, Hampton, VA
May 19-20, 1986	27th AIAA SDM Conference, San Antonio, TX
June 2-5, 1986	42nd American Helicopter Society Forum, Washington, DC
June 16-18, 1986	US National Congress of Theoretical and Applied Mechanics, Austin, TX

3. **G.A. Pierce**

January 27-28, 1986	University of Maryland, College Park, MD
April 21-24, 1986	Genrad Corporation, Laurel, MD

4. **N.L. Sankar**

June 3-4, 1986	42nd American Helicopter Society Forum, Washington, DC

5. **S.A. Meyer**

June 1-6, 1986	42nd American Helicopter Society Forum, Washington, DC

SIGNIFICANT EVENTS

Computer Programs

The following helicopter computer codes are operational and are being used in various aspects of the Center's activities.

HESCOMP/VASCOMP	NASA/Boeing Vertol	Rotorcraft Sizing and Performance
C81	ARMY/Bell Helicopter	Comprehensive Helicopter Analysis
FLYRT	Hughes Helicopters	Flight Mechanics
DNAMO5	ARMY/Bell Helicopter	Vibration Analysis
SSP1/SSP2	ARMY	Single Rotor Helo Sizing and Performance
GTR	Bell Helicopter	Tilt Rotor Flight Mechanics Program

HOVER	ARMY Structures Lab	CFD Hover Analysis
HESS/FREEMAN	NASA/USARTL Langley	Rotor-Airframe Potential Flow
VASERO	NASA Ames	Coupled potential-boundary layer analysis
DYSCO	Kaman Aerospace	Dynamic System Coupler Code
FLIGHT DYNAMICS MICROCOMPUTER CODES	NSWL/Penn State	Dynamic Behavior of Single Rotor/Tail Rotor

The Georgia Tech Center of Excellence for Rotary Wing Aircraft Technology (CERWAT) has been selected by the US Army Research Office for contract continuance for an additional year, beginning July 1, 1986. Dr. Daniel P. Schrage and Dr. David A. Peters have been added to the CERWAT faculty and are co-task investigators of Aeroelasticity Task 2, "Rotorcraft Aeroelastic Active Control Investigations."

The recent versions of the 2-D compressible Navier-Stokes solver were made available to L. Carr and J. Valdes of NASA Ames Research Center, who will be using this solver to study the effects of compressibility on the dynamic stall process. A version of this solver has also been made available to Prof. Dowell of Duke University. Prof. Dowell and his students will be using this solver to study the flutter characteristics of airfoils, using an indicial function approach.

Three student design teams comprised of CERWAT fellows and other graduate students with an interest in rotary wing engineering have entered the American Helicopter Society/Boeing Vertol National Student design competition, "A Sport Helicopter for Home Construction."

The Center and the Atlanta Chapter of the American Helicopter Society co-sponsored a very successful National Specialists' Meeting on Crashworthy Design of Rotorcraft. This meeting was in celebration of the Georgia Tech Centennial and held on the campus April 7-9, 1986. Eighty-six paid attendees were present in addition to Georgia Tech faculty and students.

The continuing education short course entitled "A Systems Approach to Advanced Rotorcraft Design and Technology Assessment" was held for the second time on the campus of Georgia Tech. Thirteen attendees from government and industry received 2.1 CEU's for successful completion of the course.

Professor John J. Harper, Professor of Aerospace Engineering, retired June 30, 1986 after 46 years at Georgia Tech. Although not supported by the CERWAT contract, Professor Harper's guidance has been invaluable during the conversion of the 7x9 foot wind tunnel to the Forward Flight Facility. This research facility is now entitled the John J. Harper Wind Tunnel.

Presentations

The following seminars were presented and well received at the Georgia Tech Center of Excellence:

"Optimum Choice of Panel Size and Collocation Points for Rapid Convergence of Lifting Line and Lifting Surface Theories as Supplied to Both Fixed and Rotating Aerodynamic Surfaces," Dan Chui, Georgia Institute of Technology, January 17, 1986.

"Evaluation of UH-60A Black Hawk Helicopter Fying Qualities Against Proposed New Military Standards, CPT Wallace D. Jenkins, USA AVSCOM, May 20, 1986.

OBSERVATIONS ON COMPRESSIVE LOCAL BUCKLING, POSTBUCKLING AND CRIPPLING OF GRAPHITE/EPOXY AIRFRAME STRUCTURE

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Abstract

Some observations based upon experimental and limited analytical studies on the local buckling, postbuckling and crippling of a thin-walled I-section composite beam are considered. The specimens are representative of airframe structure and are made of C3000/5225 graphite-epoxy woven cloth with $[0^\circ]_{4s}$, $[45^\circ/0^\circ_2/45^\circ]_s$, $[0^\circ/45^\circ_2/0^\circ]_s$, $[0^\circ]_{3s}$ and $[45^\circ/0^\circ/45^\circ]_s$ layups in the web. Warp and fill directions are assumed to be indistinguishable. They are tested in axial compression and the buckling and subsequent failure modes are recorded. Excellent correlation between the analytical and experimental buckling loads is obtained when transverse shear effects are considered. The influence of nonlinear material effects on the postbuckling behavior and the necessity to selectively include them in practical situations is discussed based upon the load-end shortening data generated. Though very small in all cases, the specimens with no angle plies exhibit higher nonlinearity.

The crippling process was monitored by high speed photography which revealed two distinct failure modes. The first one is the local material failure that is normally expected. The second one is a free edge delamination that initiates the first failure mode. The need for a unified analysis methodology encompassing the above aspects is emphasized.

COMPOSITE BOX BEAM ANALYSIS: THEORY AND EXPERIMENTS

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Abstract

Beam theory is widely used as a first approximation in numerous structural applications. When applied to composite beams, the accuracy of beam theory becomes questionable because 1) the shearing and warping deformations become significant as the shearing stiffness of composite laminates is often very low, and 2) several elastic couplings can occur that strongly influence the behavior of composite beams. The torsional behavior of thin-walled composite beams has important implications for aeronautical structures and is deeply modified by the above non-classical effects. This paper presents two comprehensive analysis methodologies for composite beams and describes experimental results obtained from a thin-walled, rectangular cross-sectional beam. The theoretical predictions are found in good agreement with the observed twist and strain distributions. Out-of-plane torsional warping of the cross-section is found to be the key factor for an accurate modeling of the torsional behavior of such structures.

POSTBUCKLING AND CRIPPLING BEHAVIOR OF GRAPHITE/EPOXY THIN-WALLED AIRFRAME MEMBERS

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Abstract

The buckling, postbuckling and crippling behavior of graphite/epoxy thin-walled I-section airframe members are studied. Test specimens are designed and fabricated using a plain woven C3000 graphite-epoxy material system. Five different ply layups $(0°, 90°, 0°, 90°)_s$, $(45°, 0°, 90°, -45°)_s$, $(0°, \pm 45°, 90°)_s$, $(0°, 90°, 0°)_s$, and $(45°, 0°, -45°)_s$, representative of those used in the aircraft industry are chosen for investigation. Buckling, postbuckling and crippling tests were conducted to determine the boundary conditions at the web/flange interface, postbuckling stiffnesses and the crippling loads and modes. Element tests were performed subsequently to generate the material property data. Nondimensional crippling curves are presented from the preliminary data which may be used for predicting crippling strengths of similar material systems. These curves are compared with the existing curves for metals. The systematic experimental approach utilized can be applied, however, even for dissimilar material systems.

DYNAMIC STALL OF OSCILLATING AIRFOILS

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Abstract

Two solution procedures are discussed for computing the dynamic stall characteristics of arbitrary shaped geometries. In the first procedure, the incompressible viscous flow equations are solved using an efficient zonal approach. The zonal approach allows the flow region to be separated into boundary layer, separated flow and potential flow regions, and solves the appropriate equations only in the vortical region. In the second approach, the compressible Navier-Stokes equations are solved on a rotating, body-fitted coordinate system. A number of incompressible and compressible flow results are presented for the light and deep dynamic stall problems, and compared with available experimental data.

SOLUTION OF THE UNSTEADY EULER EQUATIONS FOR FIXED AND ROTOR WING CONFIGURATIONS

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Abstract

A solution procedure is described for the numerical solution of inviscid rotational flow past fixed and rotor wing configurations. This procedure solves the three-dimensional Euler equations in a body-fitted coordinate system and strong conservation form. The derivatives along the spanwise direction are lagged by one time step, while all the other terms are treated in a fully implicit manner. This leads to a semi-implicit scheme that requires two block tridiagonal matrix inversions and one residual evaluation per point at every time step. This procedure also requires the flow variables to be stored at only one time level. A number of fixed wing and rotor wing calculations are presented to demonstrate the efficiency and accuracy of this procedure.

COMPUTATION OF ROTOR BLADE FLOWS USING THE EULER EQUATIONS

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Abstract

The Euler equations are used to compute steady and unsteady three-dimensional transonic flows around nonlifting rotor blades. A hybrid numerical procedure is used that treats the spanwise derivatives explicitly and the other spatial derivatives implicitly. The steady-state results are in excellent agreement with results obtained from the full potential equation. The results for unsteady flow compare well with measurements. These results demonstrate the ability of the Euler solver to compute transonic flow around helicopter blades.

EULER CALCULATIONS FOR ROTOR CONFIGURATIONS IN UNSTEADY FORWARD FLIGHT

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Abstract

A solution procedure is presented for the lifting transonic flow past modern rotor configurations in forward flight. In this procedure, the three-dimensional, unsteady Euler equations are solved in strong conservation form on a body-fitted moving coordinate system. A hybrid procedure of second order spatial accuracy and first order temporal accuracy is used to integrate the governing equations. In lifting flows, the effect of the elements of wake not captured by the computational procedure, and other aeroelastic effects are accounted for as local angle of attack corrections. Detailed comparisons with experimental data are presented for a 1/7 scale model of the Cobra OLS rotor, and for a three-bladed rotor tested in France. Some preliminary results are also presented for a three-dimensional blade vortex interaction problem.

SOLUTIONS OF THE NAVIER-STOKES EQUATIONS FOR THE FLOW ABOUT A ROTOR BLADE

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Abstract

A numerical solution procedure for solving the three-dimensional unsteady Navier-Stokes equations is described and applied to the flow over a rotor blade. This procedure solves the Navier-Stokes equations in a time accurate manner. Steady solutions are obtained by marching through time and asymptotically converging to steady state.

The procedure is a hybrid ADI scheme that has previously been applied to the solution of the Euler equations for fixed and rotary wings. The Euler solver has been upgraded to a full Navier-Stokes solver in which the viscous terms are treated explicitly in time. Explicit treatment of the viscous terms has proven successful in the past for high Reynolds number, two-dimensional flows. As with the Euler solver, the spanwise flux terms are written as a mixture of old and new time levels. The present hybrid procedure results in an efficient method, capable of handling very large time steps.

This procedure requires only one level of storage and combines some of the advantages of explicit and implicit schemes. The code is fully vectorized and operational on the CRAY X-MP at the Univ. of Illinois, National Center for Supercomputing Applications.

This method is applied to the subsonic flow of a hovering rotor blade with encouraging results. These results are compared with experimental data and Euler solutions computed by the same hybrid scheme. Cases for a tip Mach number range of 0.4 to 0.6, and Reynolds number of 10^5 to 10^6 will be investigated. Also, the effects of turbulence will be examined. The blade-vortex interaction problem for unsteady forward flight will also be investigated. To the authors' knowledge, these represent the first full Navier-Stokes calculations for a rotor blade.

BASIC RESEARCH IN STRUCTURAL DYNAMIC SYSTEM IDENTIFICATION

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Abstract

A brief review of various system identification formulations employed in structural dynamic modeling is presented. Each approach is illustrated with an example. The advantages and disadvantages of using the different formulations are discussed. Application of identification techniques to rotorcraft related problems is considered with two additional examples. Numerical results are given to demonstrate the performance of the identification procedure in each case.

MINIMUM WEIGHT DESIGN OF A STRUCTURE WITH DYNAMIC CONSTRAINTS AND A COUPLING OF BENDING AND TORSION

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Abstract

The problem of minimizing the weight of a structure subject to coupled bending and torsional vibrations and frequency constraint has been studied in this paper. Stationary values of an appropriate objective function with both linear and nonlinear constraints have been discussed. Optimal designs of thin walled open section, with and without coupling effects have been compared. The results have also been compared with those of the associated primal problem.

A COUPLED ROTOR/AIRFRAME VIBRATION MODEL WITH HIGHER HARMONIC CONTROL EFFECTS

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Abstract

A technique to identify the transfer matrix in the higher harmonic control model using a known a priori matrix is presented. The identified matrix is such that it differs the least from the a priori transfer matrix and satisfies the constraints imposed by the measured vibration levels. Application of the technique is demonstrated by using an analytical helicopter model consisting of an assumed mode rotor model and a finite element fuselage model. Results of the numerical simulations indicate that the technique could lead to significant reduction in iterations.

MECHANISM OF ENERGY ABSORPTION VIA BUCKLING: AN ANALYTICAL STUDY

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Abstract

The static post buckling behavior of energy absorbing structures has been analyzed in this paper for the purpose of developing a procedure for optimum design of energy absorbing structures which are essential parts of a crash-worthy design of rotorcraft. Finite deformations have been considered and an unadapted Lagrangian approach has been used. The numerical analysis consists of a discrete penalty function based finite element technique. The iteration procedure uses a constant arc-length method. Results have been presented for specific energy absorbing structures.